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Microwave measurement of complex permittivity and conductivity of silicon by a simple technique

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The properties of semiconductors at microwave frequencies studied earlier (Benedict & Shockley 1953, Benedict 1953, Goldley & Brown 1955) fall into two categories In the first, the semiconductor parameters were obtained from the propagation characteristics of the transmitted signal The other relates to the changes introduced by the sample inside a cavity in the resonant frequency and quality factor Montgomery (1947) From devices' point of view, the conductivity is one of the most important parameters which at microwave frequencies becomes complex. As the time period of the wave is comparable with the mean free time of carriers, the real and imaginary parts of conductivity are of the same order i.e , the relaxation effects are important The earlier workers employed dc methods to investigate the conductivity behaviour of semiconductors But these methods suffer from the limitations of using low currents to avoid heating of samples and having ohmic and surface contacts. However, microwave methods automatically overcome these difficulties

In the present paper measurements made on silicon wafers, of different resistivities, for the determination of the complex permittivity and the microwave conductivity variation with temperature are reported using a different technique.

The experimental arrangement makes use of the standard two channel bridge technique (Dube & Natarajan 1973) One arm contains a variable calibrated impedance while the other has a sample holder which is approximately a 5 cm long waveguide having a sharply cut longitudinal slot at the centre. The specimen is mounted through the slot along the axis of the waveguide wherein the electric field lies in the plane of the sample The phase shift and attenuation introduced by the specimen are measured by adjusting and readjusting the variable impedance (phase shifter and attenuator) to get null conditions in the bridge with and without the specimen. The null point is sharp and movements of quarter of a degree in phase and 0·02 db in attenuation are detectable The components of complex dielectric constant are obtained using the values of phase constant and attenuation constant (Dube & Natarajan 1973)

To study the variation of microwave conductivity of silicon with temperature, the waveguide section containing the specimen was surrounded by a small furnace designed for the purpose The furnace was constructed by winding the super kanthal wire over a glass tube nearly 6 cm in diameter and 16 cm in length Asbestos thread encircled the kanthal wire for proper insulation. The temperature of the specimen was varied by passing currents of varying strengths through the furnace with the help of a 15 amp variac and the current flowing through the circuit was read with an ammeter. The temperature of the specimen was recorded using a thermometer (0–250°C)

Table 1 contains the experimental data and calculated results for the dielectric constant and conductivity for a p-type silicon sample of dc resistivity 5·45 ohm-cm. Different thicknesses were obtained after careful etching and the uniformity in thickness varied from 2 to 4%

Table 1. Complex permittivity for a p-type silicon of resistivity 5·45 ohm-cm The measurements were taken at room temperature (310°K) and at a frequency of 9·410 GHz.

Thickness (Microns)	Phase shift per unit length (Degrees) ±0·25	Attenuation per unit length (Decibels) ±0·02	ϵ_r	ϵ_i
272	15·0	8·6	11·61±0 06	30·58±0·14
226	13·0	7·5	11·65±0·28	32·12±0·36
200	12 0	6·9	11·81±0·16	33·13±0·18
180	10·8	6 1	11·58±0·20	32·68±0·12
140	8·6	5·1	11·62±0·30	34·61±0·10
94	5·8	3·4	11·41±0·34	34·76±0·28
70	4·5	2·4	11·63±0·18	32 69±0 16

Similar measurements were taken on two other samples of silicon having resistivities 6·40 and 9·75 ohm-cm respectively To appreciate the variations of phase shift and attenuation with thickness, a few results are displayed in the form of graph in Fig. 1

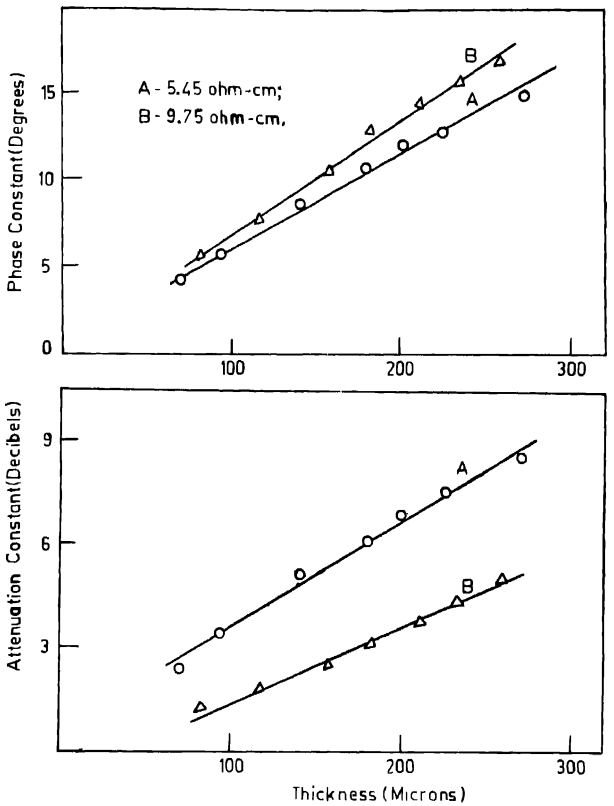

Fig. 1 Variations of phase shift and attenuation with thickness of silicon for two different resistivities.

The constancy of ϵ_r and ϵ_f with thickness as shown in Table 1 is quite expected as all these thicknesses are much higher than the mean free path of charge carriers which is of the order of a micron. Therefore, no surface effects are expected to contribute significantly As an extension of this work, however, thin film effects can be studied using this technique In that case the specimen wafter

is to be replaced by the film on appropriate substrate It must be mentioned here that the application of a tangential electric field to a thin film will necessarily involve thin film properties because the surface scattering of electrons is still a dominant phenomenon due to the random motion of electrons

The dc conductivities measured by the four probe technique and the microwave conductities obtained from the relation $\sigma_{ac} = \omega\epsilon_0\epsilon_i$, where ω is the microwave frequency of measurements, have been compared in Table 2 The real part of microwave conductities is slightly less than the corresponding dc values This is somewhat consistent with the usual expressions for ac and dc conductivities

$$\sigma_{ac} = \frac{ne^2\nu}{m[\nu^2 + \omega^2]}$$

while

$$\sigma_{dc} = \frac{ne^2}{m\nu}$$

where m, e, n and ν are the mass, charge, concentration and collision frequency of the holes

Table 2

D C conductivity by four probe technique mhos/motor	Microwave conductivity from $\sigma_{ac} = \omega\epsilon_0\epsilon_i$
10·26	9 79
15·63	15 17
18·35	17·97

The microwave data may be used to determine other transport parameters of silicon For example, the dielectric constant and conductivity in terms of effective mass m^* and relaxation time τ may be written as

$$\epsilon_r = \epsilon_L - \frac{ne^2\tau^2}{\epsilon_0 m^*[1 + (\omega\tau)^2]}$$

$$\sigma = \frac{ne^2\tau}{m^*[1 + (\omega\tau)^2]} = \omega\epsilon_0\epsilon_i$$

where ϵ_L is the lattice dielectric constant and ϵ_0 is the permittivity of free space. With the present results, the relaxation time in silicon comes out to be of the order of 10^{-13} sec, which is in good agreement with the data ($\simeq 10^{-13}$) produced by Blatt (1968)

The conductivity variations with temperature for *p*-type silicon samples (with dc resistivities 10·5, 40·0 and 170·0 ohm cm) in the temperature range 290° to 525°K are plotted as shown in Fig 2 The curves for the three silicon samples exhibit broadly similar characteristics, viz, the conductivity initially decreases with increase of temperature and afterwards increases very rapidly with temperature This is of course as expected considering the relative predominance of extrinsic and intrinsic conduction mechanisms. The conductivity of the samples (having resistivities 10 5 and 40·0 ohm-cm) decreases from room temperature to 440°K. In this temperature region the lattice scattering by acoustical phonons plays the dominant role (Blakemore 1969). As the temperature is raised further, the concentration of free electrons and holes increases and the intrinsic conduction predominates thereafter In the case of the third sample (170 0 ohm-cm, the highest resistivity of all the three), the conductivity rises slowly from the room temperature upto 440°K and increases very rapidly afterwards thereby showing its intrinsic behaviour from the room temperature itself Bhar (1963) made similar measurements on temperature variations of microwave conductivity for bulk *p*-type silicon samples having conductivities 0·7 mho/meter and 0 1 mho/meter in the temperature range 273 to 480°K The curves for the conductivity variation with temperature resemble that of the curves shown in Fig. 2.

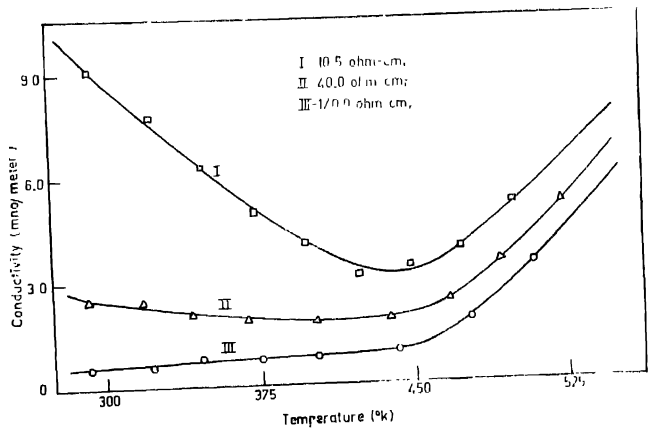

Fig. 2. Microwave conductivity variation of silicon wafers in the temperature range 293–523°K.

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E.S.R. and optical absorption studies on two copper (II) Schiff-base complexes in solutions

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As a part of our general programme to study stereochemistry and metal ligand bond nature of organo-metal complexes in solutions by physical methods, we have taken up the E S.R. and optical absorption studies of two copper(II) Schiff-base complexes (Healy *et al* 1975) formed by the condensation of 3,3′-(iminobis-propylamine) and 2-hydroxy-5-methylbenzophenone (hereafter referred to as Cu(mbp)) and 5-chloro-2-hydroxybenzophenone (hereafter referred to as Cu(cbp)). Crystal structure is available only for the former complexes (Healy *et al* 1975) From the crystal structure of this complex it is found that it is a five co-ordinate monomer formed with three nitrogen atoms and two oxygen atoms arranged in a distorted square pyramidal fashion. In this communication an attempt has been made to find out whether the coordination around copper(II) ion and the crystal structure of these complexes are same by comparing the E.S R. and optical absorption data of these complexes in solutions and powders respectively The E.S.R spectra of both the complexes in solutions of benzene, dioxane, pyridine and powders are recorded with the help of a varian E-4 x-band E.S R spectrometer using E-231 resonant cavity The errors in the calculations of g and hyperfine separation (A) will be about $\pm 0{\cdot}0005$ and $+0{\cdot}5$G respectively Optical absorption spectra of these complexes in solutions are recorded with a